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Comparison of Two Navy Environmental Database Models:

Generalized Digital Environmental Model and Podeszwa Sound Speed Profile Model

by Morris Schulkin

Technical Report
APL-UW TR 8926
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Applied Physics Laboratory University of Washington
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ABSTRACT

We review the construction of the Generalized Digital Environmental Model (GDEM), the Navy standard for modeling sound speed profiles, and the Podeszwa sound speed profile model which has been used by the Naval Underwater Systems Center. GDEM, developed by the Naval Oceanographic Office, derives vertical profiles of temperature and salinity in $30' \times 30'$ latitude-longitude grid elements and employs these data to calculate sound speed profiles. The temperature-salinity profiles are derived from quality-screened data from the Master Oceanographic Observation Data Set maintained by the Fleet Numerical Oceanography Center. Podeszwa uses temperature-salinity data from deep Nansen casts and organizes the calculated SSPs into provinces based on temperature-salinity water mass characteristics. In spite of the differences in their construction, the two models are found to be essentially equivalent in principle.

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I. INTRODUCTION

Two environmental models based on oceanic databases have been used to provide steady-state (climatological) profiles of sound speed in the ocean for Navy applications: The Generalized Digital Environmental Model[1] (GDEM) and the Podeszwa sound speed profile (SSP) model. GDEM was developed by the Naval Oceanographic Office (NAVOCEANO) for general Navy applications. The Podeszwa SSP model was developed for the Naval Underwater Systems Center (NUSC) for use in the Sonar In-Situ Mode Assessment System (SIMAS),[2] a tactical range-prediction system for submarines and surface ships. Both models depend on the thermohaline properties of water masses (temperature and salinity vs depth) but use different types of data sets. GDEM uses a quality-screened subset of all information on temperature and salinity profiles that is in the Master Oceanographic Observation Data Set (MOODS) maintained by the Fleet Numerical Oceanography Center. These data are grouped into three depth intervals for $30' \times 30'$ latitude-longitude grid elements and merged into representative vertical profiles of temperature and salinity which are then used to derive sound speed profiles. Podeszwa uses all available deep Nansen casts from the National Oceanographic Data Center in which the temperature and salinity data were obtained simultaneously. He computes sound speed profiles directly for each water mass type. These profiles are assembled by subtype to form sound speed provinces for five major ocean areas.[3–7]

The author was requested to review existing information on these two methods to answer the following questions concerning GDEM and the Podeszwa SSP model:

(a) "Is there a valid technical concern over the construction of GDEM to satisfy submarine and surface ship sensor requirements?"

(b) "If there is a technical problem in GDEM, would it cause inaccurate ranges to convergence zones or other serious propagation loss errors in terms of tactical requirements?"

(c) "What are the old SIMAS data base (Podeszwa) errors in terms of the same tactical requirements? (SIMAS is the NUSC prediction system.)"

(d) "If GDEM does have serious technical problems, does the old SIMAS SSP (NUSC) data base, or any other, provide a more accurate representation of the historical SSP?"

To summarize the results of this study, it was found that the construction of GDEM is technically valid, and its use should result in predictions of convergence zone range that satisfy the accuracy requirements for submarine and surface ship sensors.

II. BACKGROUND

Models of sound speed based on oceanic databases may be constructed in different ways to satisfy various oceanographic requirements. GDEM and the Podeszwa model developed for SIMAS employ two quite different approaches to satisfy sonar tactical prediction requirements for surface ships, submarines, and aircraft. Until recently, the Podeszwa SSP model was used for surface ship and submarine tactical requirements whereas a derivative of GDEM was used for aircraft ASW tactical requirements. Both approaches employ the concept of stable ocean water masses. Podeszwa used sound speed as the water mass parameter whereas GDEM uses density or σ_T: $\sigma_T = (\rho - 1) \times 10^3$, where ρ is the density of seawater referenced to standard atmospheric pressure. Temperature, salinity, and depth (pressure) are parameters used to calculate both density and sound speed profiles. If the same measured values are used for these parameters, then either type of profile is representative of that water mass. Variability—which occurs in the near-surface layer (0–400 m) and deeper in currents, countercurrents, eddies, and pycnocline waves—is accommodated differently by each type of model, using measured data and suitable merging techniques.

Podeszwa categorized the sound speed profiles into as few provinces as possible using as criteria the similarity of depth dependence and a maximum difference of 4–6 ft s^{-1} within the same province at 1200 ft depth and 6–10 ft s^{-1} between profiles of contiguous areas at 1200 ft depth. SIMAS with the Podeszwa SSP province model was developed for surface ship and submarine sonar systems to which it has been applied for many years. SIMAS led to the successful design and development of sonar systems, training of operators, and the operational deployment of these systems.

GDEM has been applied successfully to all other Navy systems, including systems for deploying sonobuoys from aircraft, the Tactical Environmental Support System (TESS), and the Integrated Command ASW Prediction System (ICAPS).[8] In GDEM oceanographic data are assembled in $30' \times 30'$ latitude-longitude grid elements for the entire ocean. The basic data are tables of temperature, salinity, and depth in three separate depth intervals from the ocean surface to the ocean bottom. The coefficients of specific modeling functions are then determined so that the functions predict values that agree with the GDEM basic data to within a specified error. Vertical profiles of density are calculated and checked for stability. If this test is satisfied, then temperature and salinity profiles are converted to sound speed profiles. For the rare cases where a density inversion appears, a new value of salinity is used to correct this instability.

Both of the environmental databases use temperature-salinity profiles as water mass identifiers and are equivalent in principle. GDEM, however, is more flexible: the GDEM data can be converted to sound speed profiles directly, whereas the Podeszwa SSP data cannot be readily converted to density or stability profiles.

III. WATER MASSES AND THERMOHALINE RELATIONSHIPS

A slow, density-driven vertical circulation exists in the ocean which leads to stable density layering, or stratification. The deep water layers of all oceans are derived from the polar regions and have about the same temperature and salinity characteristics as the surface waters of those regions. This permanency in gross vertical structure allows identification of water masses from their vertical temperature and salinity structure.

When these vertical distributions are plotted with temperature and salinity as the coordinates and σ_T as a parameter, the resulting curves are called T-S curves. Figure 1 shows T-S curves for principal water masses of the oceans. Note that the curves are distinctly different. Figure 2 shows the geographical distribution of the upper water masses of the world's oceans as classified by their T-S curves.

Both sound speed and density are water mass properties. They are functions of temperature, salinity, and pressure (depth). The values of temperature and salinity obtained for a vertical profile in a given water mass should give consistent profiles when converted to sound speed or density. Podeszwa subdivided the principal water mass provinces to derive his sound speed provinces in both horizontal and vertical extent. GDEM uses $30' \times 30'$ "points" for which it derives temperature-vs-depth and salinity-vs-depth profiles which are then used to calculate sound speed profiles.

As an example of the connection between Podeszwa's atlases and water mass provinces, Figure 3 shows his SSP provinces for the North Pacific Ocean[3] overlain with a line depicting the acoustic path between Honolulu and San Francisco. Table 1 shows how Podeszwa's provinces are subdivisions of established water mass classes. The sound speed provinces designated in the table correspond to those on the chart.

IV. CONSTRUCTION OF ENVIRONMENTAL DATABASE MODELS

The approaches used in constructing GDEM and Podeszwa's SSP model have both differences and similarities. One of the main differences is the content of the databases. Podeszwa used Nansen cast data (from the National Oceanographic Data Center) which had been taken to the bottom. Extensive coverage was sacrificed for consistency and reliability. The Podeszwa model is not meant to be updated. It emphasizes the conservative nature of the ocean.

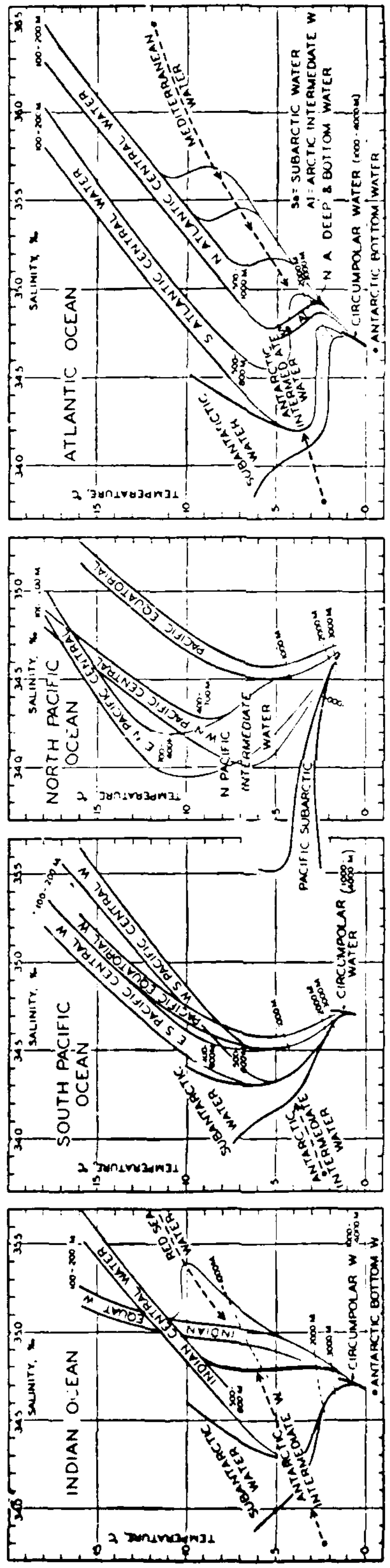

Figure 1. Temperature-salinity relations of the principal water masses of the oceans. [from Ref. 9]

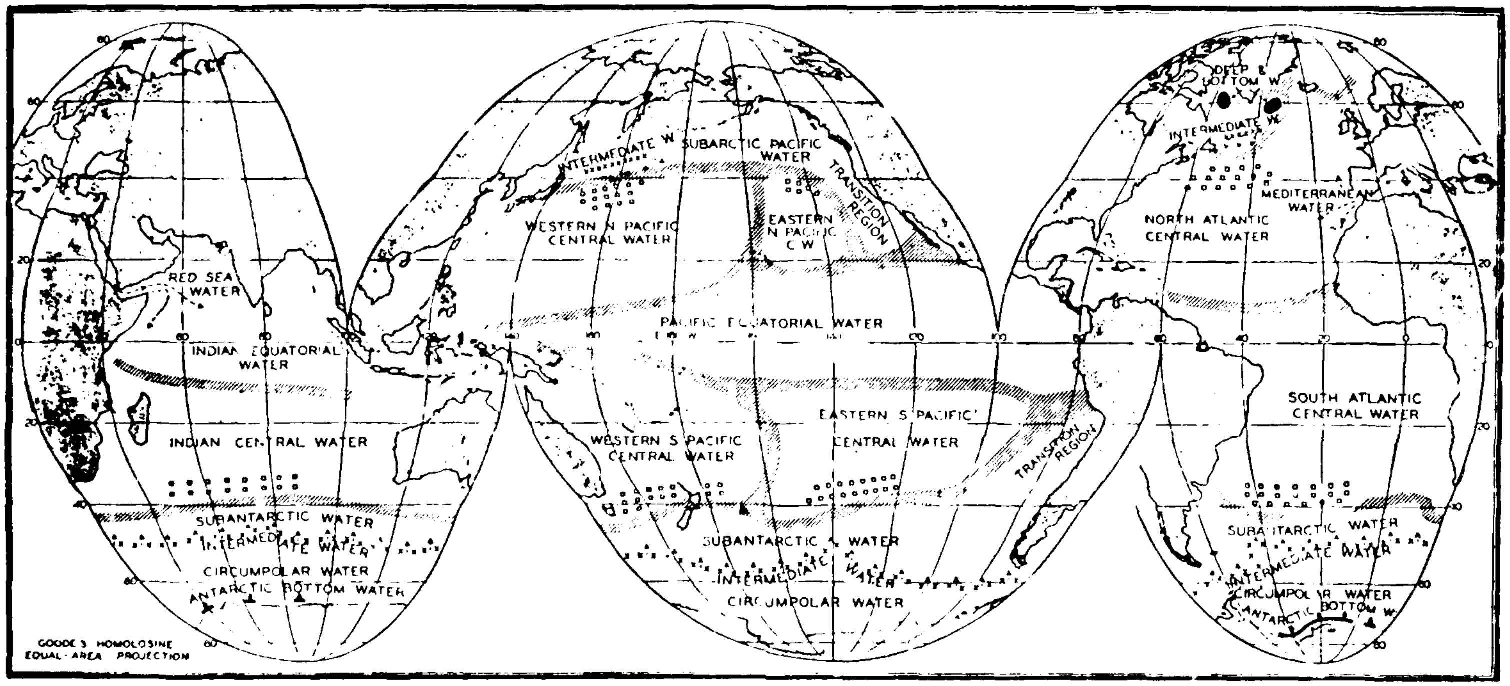

Figure 2. The geographic distribution of the upper water masses that have common vertical salinity and temperature distributions, as denoted by their T-S curves. Squares mark the regions in which the central water masses are formed; crosses indicate the lines along which the antarctic and arctic intermediate waters sink. [from Ref. 9]

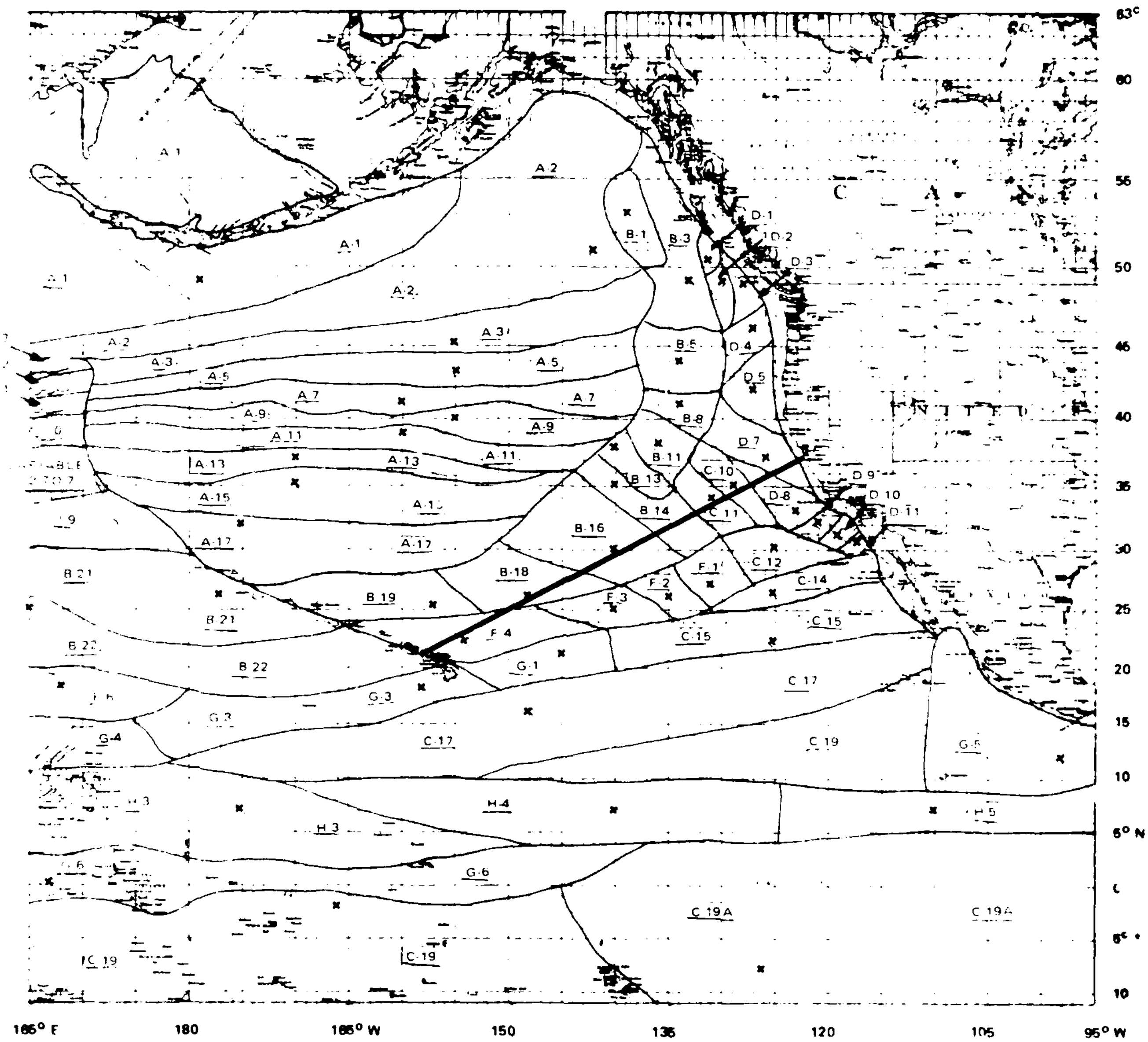

Figure 3. Location chart of representative sound speed profile structure for Central and Eastern North Pacific Ocean from 0 to 4500 ft. The solid straight line shows the provinces traversed by an acoustic path between Honolulu, Hawaii, and San Francisco, California. [adapted from Ref. 3]

Table 1. Relation between North Pacific water mass classes and Podeszwa sound speed profile provinces (acoustic path is between Honolulu, Hawaii, and San Francisco, California, as shown in Figure 3).

Distance Along Path	Sound-Speed-Profile Province (Podeszwa)	Water Mass Class
0– 949 km	F-4	Eastern North Pacific Central Water
949–1755 km	B-18	
1755–2480 km	B-16	Northeast Pacific Transition Zone
2480–2889 km	B-14	
2889–3210 km	C-11	
3210–3380 km	C-10	California Current (Modified Subarctic Water)
3380–3570 km	D-8	
3570–3835 km	D-7	

The data set used to develop the GDEM mean profiles was derived from several sources. These include quality-screened sets of expendable bathythermograph data, hydrocasts (Nansen casts) from ocean stations, salinity-temperature-depth (STD) data, and some mechanical bathythermograph measurements primarily from the Fleet Numerical Oceanography Center. Master Oceanographic Observation Data Set files for 1985 were used as well as files from the NAVOCEANO Oceanographic Data Set for 1985. GDEM can be updated at any time, typically adding thousands of points to the data set.

Both models use three overlapping depth intervals to describe their mean data fields. Podeszwa uses simultaneous temperature and salinity measurements to calculate sound speed profiles whereas GDEM uses the data obtained from the fitted temperature and salinity fields from diverse sources. The construction procedures are summarized briefly below.

A. Podeszwa SSP Model

In devising his sound speed province model for the North Pacific, Podeszwa made some assumptions, based on observation and water mass analysis, about the appropriate depth intervals to be used and their temporal variability.[3] He found that he could use three general depth intervals and merge the data smoothly by overlapping the curve-fits in their construction.

(a) Near-Surface Model: Surface to 4500 ft (1371 m)

Charts are provided by month within each province specifying subareas of typical SSP structure for 0–4500 ft (1371 m).

(b) Mid-Depth Model: 1500 ft (457 m) to 7000 ft (2133 m)

Data are grouped so that annual average profiles at specific locations in the group show little or no variation in temperature at depths below 1250 ft (381 m). At 1200 ft (366 m) the separation in sound speed within groups is 4–6 ft s^{-1}; at 1500 ft (457 m) it is smaller. Mergers with near-surface data are to be made preferably at 1500 ft (475 m); otherwise 1200 ft (366 m) is used.

(c) Deep Model: 7000 ft (2133 m) to 21,000 ft (6400 m)

A single, annually averaged profile is used at depths below 7000 ft. All sound speed profiles are identical down to 21,000 ft (6400 m).

B. GDEM

GDEM was designed to produce mean seasonal or monthly fields of temperature, salinity, and sound speed on a $30' \times 30'$ latitude-longitude grid of the ocean.[1,11] Similar to Podeszwa's model, it uses three overlapping depth intervals with specified temporal behavior for each depth interval (see Figure 4).

(a) Near-Surface (Shallow Top) Model: 0 to 400 m (1313 ft)

The near-surface (Shallow Top) temperature model is expressed seasonally or monthly. The salinity model is expressed for 5-month seasons in which the adjacent months are added to both ends of each 3-month season. The sound speed model can be expressed seasonally or monthly. A unique curve-fitting technique is used in combining the data for each depth interval to arrive at a historical ocean profile for a given location. This merging technique was required by the different functional representation in each depth interval and the disproportionately large number of data points for the near-surface model compared with the other two depth intervals.

(b) Mid-Depth Model: 200 m (657 ft) to 2450 m (8038 ft)

The temperature and salinity models are expressed as biseasonal (semiannual) mean data fields. The mid-depth sound speed model is derived for biseasonal application.

(c) Deep Model: 2000 m (6562 ft) to bottom

The deep temperature, salinity, and sound speed profiles are expressed as an annual mean of the data fields. They are fitted as a quadratic function of depth.

The merging technique[12] used in the development of the GDEM is described in the following section.

Submodel Type	Submodel Form
• Shallow top	
Temperature	8 coefficients, nonlinear
0-400 m	least-squares
3-month seasons	RMS error of fit < 0.5°C
1-month sea-surface	(1.80 m/s)
Salinity	5° orthogonal polynomial
0-400 m	RMS error of fit < 0.1‰
5-month seasons	(0.12 m/s)
• Mid Depth	
Temperature	7° orthogonal polynomial
200-2450 m	RMS error of fit < 0.25°C
6-month seasons	(0.90 m/s)
Salinity	5° orthogonal polynomial
200-2450 m	RMS error of fit < 0.05‰
6-month seasons	(0.06 m/s)
• Deep	
Temperature	2° quadratic
2000 m-bottom	RMS error of fit < 0.25°C
12-month seasons	(0.90 m/s)
Salinity	2° quadratic
2000 m-bottom	RMS error of fit < 0.05‰
12-month seasons	(0.06 m/s)

30′ × 30′ spatial grid of coefficients for each environmental submodel generated by a two-dimensional cubic spline process

Merge shallow and deep models with mid-depth models to produce primary models surface to bottom, 3-month seasons with 1-month option, on a 30′ × 30′ spatial grid

Products

Figure 4. The Generalized Digital Environmental Model (GDEM). [adapted from Ref. 1].

V. GDEM T-S PROFILE MERGING

A. Near-Surface (Shallow Top) and Mid-Depth Merger

The near-surface (Shallow Top) and mid-depth profiles are adjusted in the merging procedure. If the difference in temperature at 400 m is less than 0.25°C, only the mid-depth profile is modified. If the difference is larger than 0.25°C, the top profile is also changed. For differences between 0.25°C and 0.5°C, the top profile absorbs half the difference. For differences greater than 0.5°C, the top profile absorbs all the difference in excess of 0.5°C. The top profile is modified from 400 m upward, the mid-depth profile downward. The modification technique is the same for each except that the modification to the top profile decays more rapidly. The corrected temperature at any given depth, D, is

$$T_{\text{new}} = T_D + \alpha \Delta T (0.835)^{\beta} ,$$

where

$$\begin{aligned}
T_{\text{new}} &= \text{merged temperature at depth } D \\
T_D &= \text{model temperature at depth } D \\
\alpha &= \text{percent } \Delta T \text{ assigned to merger} \\
\Delta T &= \text{difference in temperature at merger depth} \\
&= T_{\text{mid}} - T_{\text{top}} \text{ for top merger} \\
&= T_{\text{top}} - T_{\text{mid}} \text{ for mid merger} \\
\beta &= \delta \, | D - \text{merger depth} \, | \\
\delta &= \text{scaling factor} \\
&= 0.01 \text{ for mid-depth model} \\
&= 0.05 \text{ for top model.}
\end{aligned}$$

NOTE:

$$(0.835)^{\beta} = \begin{cases} e^{-(D-D_m)/554.6} & \text{for mid-depth model} \\ e^{-(D-D_m)/110.9} & \text{for top model} \end{cases}$$

where D_m is the merger depth.

After the top and mid-depth merger is made, the merged values for 400 and 500 m are removed, and a natural spline is fit to the remaining values from the surface to the bottom of the mid-depth model. New interpolated values for 400 and 500 m are estimated by evaluating the spline at those depths.

B. Deep Merger

The merger between the mid-depth and deep profiles is similar to the previous merger except that the difference is taken at 2000 m and the correction is applied only upward from 2000 m on the mid-depth profile. The correction decays twice as fast ($\delta = 0.02$) as the downward correction of the upper merger. This merger is actually done before the upper merger, and the corrections are always small.

Table 2 shows the correction for a starting difference ($T_{mid} - T_{top}$) of 1°C at the merger depth of 400 m. This is the largest correction that is allowed to the mid-depth model.

Table 2. GDEM corrections for a starting difference of 1°C at the merger depth of 400 m.

Shallow Top Submodel		Mid-Depth Submodel	
Depth (m)	Correction (°C)	Depth (m)	Correction (°C)
0	+0.01	400	−0.50
10	+0.01	500	−0.42
20	+0.01	600	−0.35
30	+0.02	700	−0.29
50	+0.02	800	−0.25
75	+0.03	900	−0.20
100	+0.03	1000	−0.17
125	+0.04	1100	−0.14
150	+0.05	1200	−0.12
200	+0.08	1300	−0.10
250	+0.13	1400	−0.08
300	+0.20	1500	−0.07
400	+0.50	1750	−0.04
		2000	−0.03
		2500	−0.01
		3000	0.00

A study was made[12] of typical differences between the model predictions and the actual data when the top and mid-depth models were merged. The number of mergers made (i.e., the number of grid cells used by GDEM) for the North Atlantic in one season is 16,091. Table 3 shows the differences before the merger for the summer season (which is similar to that for other seasons). The temperature-difference distribution at 400 m depth is summarized in Figure 5. It is estimated that 70% of the cases have a temperature difference ≤0.5°C.

Table 3. Differences between GDEM values and actual data before the shallow top and mid-depth merger (North Atlantic, Summer).

Summer Temperature

Difference (°C)	Number of Occurrences
0 to 1	14190
>1 to 2	1393
>2 to 3	301
>3 to 4	128
>4	79

Summer Salinity

Difference (ppt)	Number of Occurrences
0.0 to 0.2	15196
>0.2 to 0.3	532
>0.3 to 0.5	269
>0.5 to 0.8	85
>0.8 to 1.0	7
>1.0	2

Summer density inversions after the merger that required additional fine adjustment to the salinity models

Difference (ppt)	Number of Occurrences
>0.2 to 0.3	16
>0.3 to 0.5	9
>0.5	0

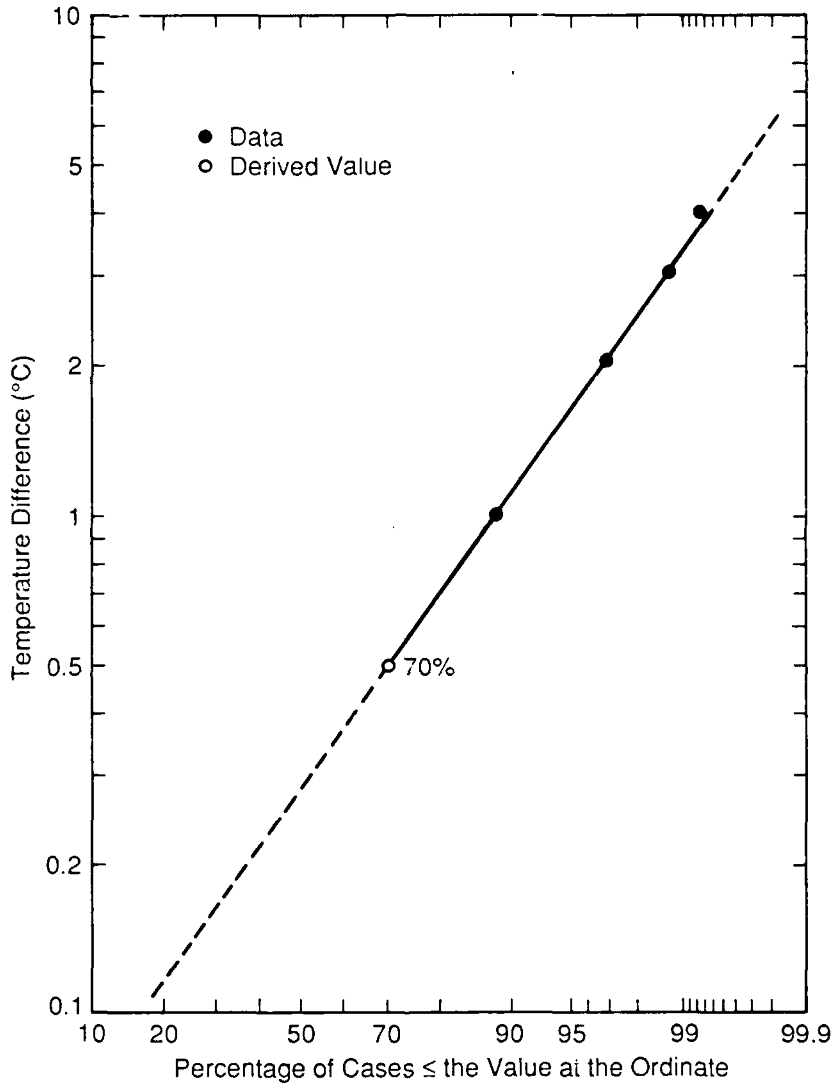

Figure 5. Cumulative distribution of GDEM temperature differences between the Shallow Top and Mid-Depth submodels before correction at 400 m depth (North Atlantic, Summer). [constructed from data in Table 3]

VI. VALIDITY CRITERIA

A. NUSC Runs to Determine Convergence Zone (CZ) Range

The Podeszwa SSP model defines province boundaries in terms of magnitude of differences in sound speed and sound speed gradients from one province to another. Tactical parameters, such as the range to a convergence zone, can be computed and the error in prediction then determined for each province. Most of the Podeszwa SSP provinces have been constructed so that there is an error of ±1 kyd in predicting the range to a convergence zone. To check this accuracy, data were analyzed from a limited set of 16 "leading-edge" runs in which an alerted surface ship monitored the first appearance or disappearance of the echo from a submarine as it moved through the limiting ray of the convergence zone; it was verified that the probable error of measurement was 1.1 kyd.[13] Since this performance meets the specification of about 1 kyd for probable error, a favorable comparison of predictions made using GDEM and the Podeszwa SSP model would imply their essential equivalence.

B. Comparison of CZ Range Predictions Using GDEM and the Podeszwa Model

GDEM fits its database to within a specified acceptable error to generate profiles of temperature and salinity vs depth for $30' \times 30'$ latitude-longitude points. Provinces can also be determined within a stated error either in terms of correlation of sound speed profiles or in terms of sonar performance parameters, e.g., ±1 kyd for convergence zone range. The author is unaware of alerted surface ship or submarine tests for GDEM, but there is a NUSC study comparing the use of Podeszwa and GDEM CZ range predictions on a random sampling basis for each of the oceans and any month.[14] The comparison considers estimates of layer depth as well as predictions of convergence zone range.

For this comparison, NUSC used a computer-stored version of the Podeszwa SSP database. The GDEM profiles were drawn from the Oceanographic and Atmospheric Master Library.[11] The profiles were stored as a function of latitude, longitude, and month. The two key prediction parameters chosen for comparison were the estimated layer depth and the computed range to a convergence zone via the limiting ray between source and target.

Because almost 1000 locations were used in the NUSC study, convergence zone range was defined in terms of a ray-trace algorithm from the RAYMODE transmission-loss computer program. Nine-hundred and eighteen test cases were selected at random from the North Pacific, North Atlantic, Mediterranean, Norwegian Sea, and Indian Ocean. The results can be stated simply in terms of cumulative distributions.

Independent of layer depth, 83% of the computed convergence zone ranges agreed within 3 kyd and 50% agreed within 1.2 kyd (see Figure 6). These results compare well with the measured error in the NUSC leading-edge runs. This was a stringent test, since the latitude-longitude points were $30' \times 30'$ grid elements for GDEM and large provinces were used for the Podeszwa SSP model for the five oceans. Furthermore, the months were chosen at random.

Of the layer-depth predictions, 50% agreed within 18 yd at a given location for any month of the year; 70% agreed within 33 yd (see Figure 7). Interestingly, the same cumulative distribution was found for the spatial variation of layer depth for the month of April across the 16 Podeszwa provinces between Honolulu and San Francisco (3855 km). Thus it would seem that the same oceanwide disturbances are manifested locally.

The differences in the predictions of convergence zone range are acceptable for tactical applications based on the concept that (a) the figure-of-merit differs by several decibels from system to system and from platform to platform with the same system, (b) random target aspects introduce a variability of several decibels, and (c) the target could use local conditions to hide. Once detection is achieved, however, weapons could be deployed with much improved range accuracy. In several of the exercise runs, detection and location took almost an hour for a target known to be in the convergence zone. Tactical uses that are made of convergence zone range predictions are (a) selecting a sonar search mode, (b) setting the 20-kyd-wide convergence zone range scale for active sonar, and (c) estimating the initial range for bearing-time solutions for passive sonar.

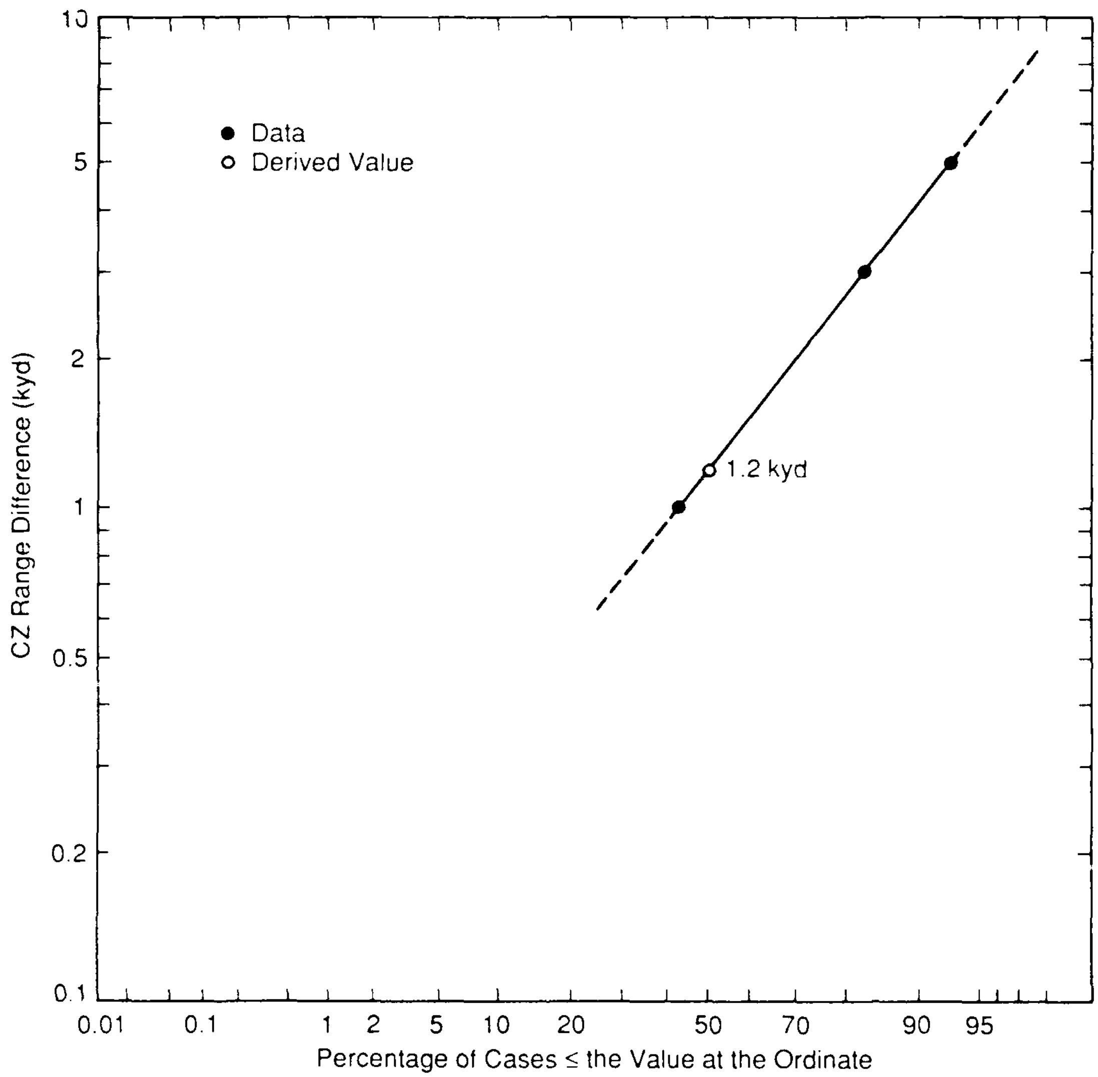

Figure 6. Cumulative distribution of computed differences in convergence zone range using GDEM and Podeszwa SSP model. Data are for months chosen at random and 918 locations from five ocean areas. A RAYMODE ray trace algorithm was used for computing convergence zone range. [constructed from data in Ref. 14]

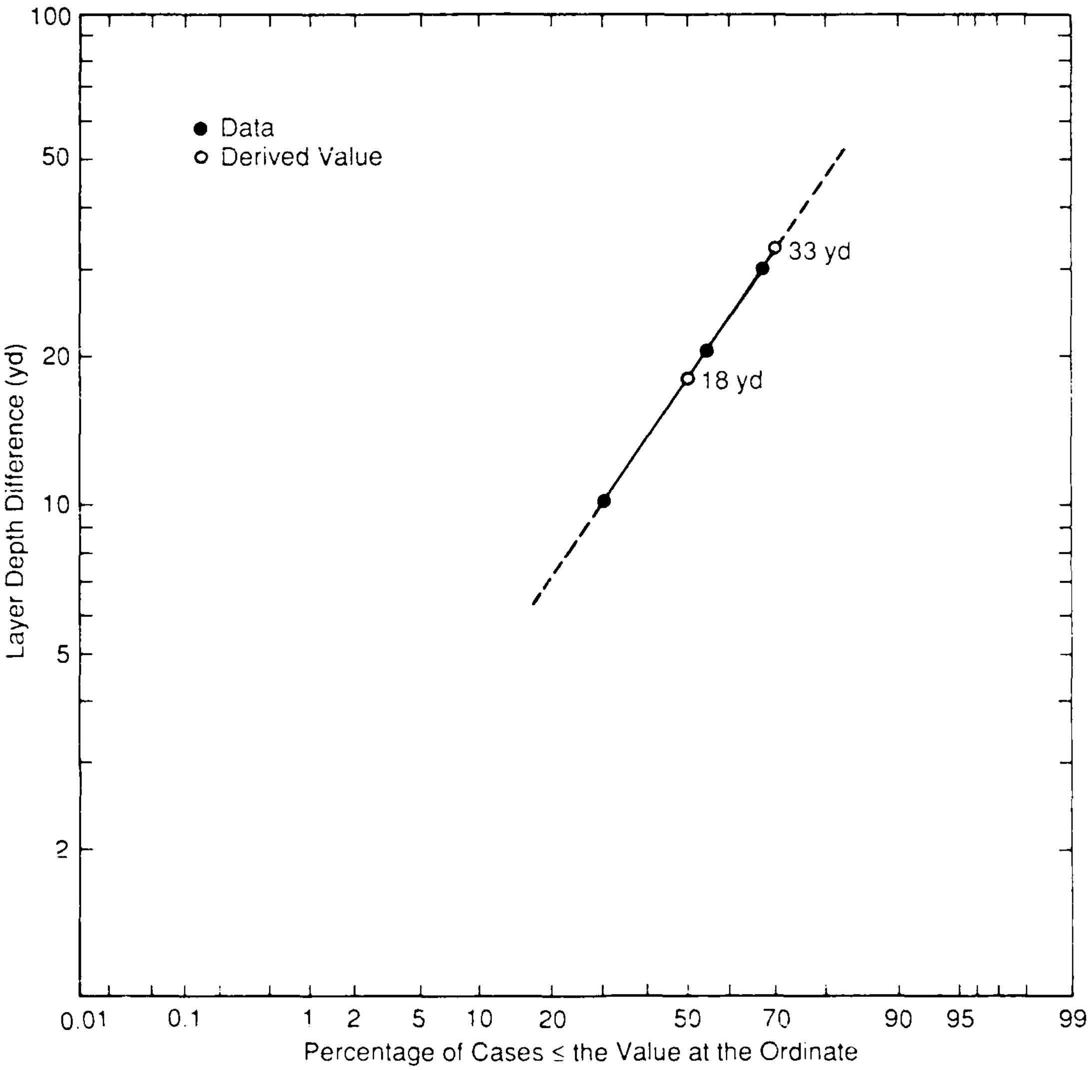

Figure 7. Cumulative distribution of differences in layer depth estimated using the Podeszwa SSP model and GDEM [constructed from data in Ref. 14]

VII. CONCLUSIONS

One of the great accomplishments of Podeszwa was his production of SSP province atlases for five oceans. They were used tactically, for training, and for operational planning. Use of Podeszwa's atlases is now being phased out in favor of GDEM, whose gridded format facilitates the objective production of province- or contour-type atlases[1,15] of many types to fit various oceanographic or tactical requirements. Derived quantities such as dynamic height, sound speed, σ_T, and stability can also be computed. Provinces based on the shape of the sound speed profile have been produced as well as historical ocean provinces which provide contours of convergence zone ranges to within 1 kyd. As noted in the Introduction, however, several questions have been raised in regard to the accuracy of the GDEM predictions.

Based on the comparisons reported here, the four questions asked in the Introduction can be answered as follows:

(a) The construction of the Generalized Digital Environmental Model is technically valid. It fits vertical profiles of temperature and salinity from one depth interval to another within specified error bounds and satisfies ocean water mass density stability requirements. The sound speed profiles determined from these temperature-salinity profiles should meet submarine and surface ship sensor requirements.

(b) There is no technical problem with GDEM with regard to determining environmental parameters for tactical requirements.

(c) The Podeszwa sound speed profile database is consistent and reliable for tactical sonar use. One set of 16 alerted leading-edge runs shows a probable error of 1.1 kyd in measuring the range to a convergence zone.

(d) GDEM does not have serious technical problems.

VIII. RECOMMENDATION

It is recommended that the Navy continue to use GDEM as a valid model for accommodating ocean spatial and temporal variability on all scales.

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We review the construction of the Generalized Digital Environmental Model (GDEM), the Navy standard for modeling sound speed profiles, and the Podeszwa sound speed profile model which has been used by the Naval Underwater Systems Center. GDEM, developed by the Naval Oceanographic Office, derives vertical profiles of temperature and salinity in 30′ × 30′ latitude-longitude grid elements and employs these data to calculate sound speed profiles. The temperature-salinity profiles are derived from quality screened data from the Master Oceanographic Observation Data Set maintained by the Fleet Numerical Oceanography Center. Podeszwa uses temperature-salinity data from deep Nansen casts and organizes the calculated SSPs into provinces based on temperature-salinity water mass characteristics. In spite of the differences in their construction, the two models are found to be essentially equivalent in principle.

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Profile merging techniques
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Sound speed profile
Sound speed profile atlases
T-S curves
Convergence zone range
Layer depth
Density stability
Podeszwa sound speed profile atlases